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Renewable energy sources policies in a Bayesian DSGE model

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ABSTRACT

Environmental policy measures to reduce greenhouse gases emission to mitigate climate change are common practice in many developed countries, encompassing both technology-push measures and demand-pull measures. The effectiveness of such policies continues to need investigation, especially when shortsighted measures lead to suboptimal investments in the absence of a credible government commitment. The aim of this paper is to assess the effectiveness of a comprehensive strategy for renewable energy sources in a dynamic stochastic general equilibrium model estimated for the Euro area using Bayesian estimation techniques, which includes carbon tax and subsidy measures. To this end, we compare the cost-effectiveness of technology-push measures and demand-pull measures. Our findings show that the environmental policy based on technology-push measures may produce better dynamic effects than demand-pull measures based on a subsidy policy of equal monetary amount. In fact, RES price parity is estimated to occur sooner by implementing technology-push measures than demand-pull measures.

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1. Introduction

There is an ongoing debate on environmental policies' effectiveness in addressing climate change. In many countries around the world, policies to raise the share of renewable energy sources (RES) have been implemented as part of the global response to climate change [2,49,58].

European Union (EU) countries have provided support for the development of RES, dating back to as early as the 1990s. In 2014, the EU has defined new challenging goals for the year 2030, through the implementation of the 2030 Energy Strategy: a 40% cut in greenhouse gas emissions compared to 1990 levels, at least a 27% share of RES consumption, and at least 27% energy savings compared with the business-as-usual scenario. This Strategy provides the definition of new forms of governance, allowing greater synergy among member countries.

However, several barriers prevent RES deployment, such as cost-effectiveness, technical barriers, and market barriers [23]. The environmental innovation literature splits policy instruments in two main categories, that are technology-push and demand-pull instruments [36,43]. Technology-push is a supply-side driven mechanism based on the argument that advances in scientific understanding determine the rate and direction of innovation [11]. Technology-push instruments for RES technologies are generally implemented as direct support to capital investment in the RES sector, such as public research and development (R&D) spending, fiscal measures that support private R&D. It is an important mechanism that internalize the benefits from innovations in climate-friendly technologies, such as RES [16]. By contrast, demand-pull instruments aim at increasing RES use through market-based approaches, such as renewable portfolio standards, quotas, supportive tax policy, and command-and-control measures, such as technology standards [19,34]. Both mechanisms have been used to justify the implementation of public policies stimulating RES development. The interactions between technology-push and demand-pull measures are heavily debated in the literature, considering the two mechanisms on the one hand as mutually exclusive and, on the other hand, complementary (see among others [3]).

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The aim of this paper is to investigate the relative effectiveness of a comprehensive cost-effective strategy for RES deployment based on technology-push and demand-pull measures in the Euro area. Besides, we analyze grid parity dynamics across the EU. We estimate a dynamic stochastic general equilibrium (DSGE) model using Bayesian techniques. The inferential procedure adopted is based on Markov Chain Monte Carlo methods (MCMC), which are able to estimate not only the model parameters but also the dynamics of some relevant variables (i.e., fossil fuels and RES prices). Our model is estimated on EU-15 data from 1995 to 2014. The focus here is on three non-hydro RES, i.e., wind, solar photovoltaic and biomass. The proceedings of the carbon tax are used to finance the RES policy. The model captures the proposal by Grimaud et al. [32]; which shows that two instruments—a subsidy to knowledge capital and a carbon tax—are necessary to correct for the two market failures, i.e., R&D spillovers and pollution.

RES are challenging for safety and security aspects, energy independence and low carbon emissions [6,21]. Wind and solar photovoltaic, driven by the wind and the sun, are quite well distributed throughout the world and do not diminish as they are used. Besides, they have not fuel costs, so their price cannot fluctuate as fossil fuels' prices, which are volatile and subject to geopolitical conditions. Unfortunately, RES, and specifically wind and solar power, cannot produce steady electric power because they characterized by intermittent behaviors, i.e., wind speed and direction change due to weather conditions, and solar irradiance depends on the time of the day and clearness of the sky [37]. However, the use of energy storage technologies represents a great opportunity for overcoming RES intermittent characteristics, allowing the correction between the supply and demand of available energy [44]. Biomass can play an important role in balancing wind and solar photovoltaic energy because it can be stored at times of low demand and provides energy when needed [24]. Biomass energy, mainly wood, agricultural and urban waste, if produced in a sustainable way, can be used for heating, electricity generation, and transport fuels.[1]

Designing successful schemes for RES development is fundamental to reach price parity, i.e., the point at which RES technologies become competitive with fossil-fuel-based technologies, without any further need of public support [47]. Much literature is investigating price parity. Fokaides and Kylili [29]; stating that Cyprus has already reached solar photovoltaic price parity, examined the conditions for achieving it in insular energy systems. Campisi et al. [14] found that grid-parity in the wind sector has not achieved in Italy, and its achievement will depend from the wholesale energy prices, the financial framework and investment costs. Breyer and Gerlach [12] presented a model applied to more than 150 countries in the world, which, taking into account experience curves, photovoltaic system cost, growth rate of photovoltaic industry, electricity prices, forecast price parity to be achieved within 2022.

Short-term policy measures might cause suboptimal private investment if perceived as unstable. Indeed, several recent turnabouts in climate-change policies offer only shaky financial support to RES [10,35]. An unstable situation may lead to change in investors' decisions that in turn influence RES′ price parity achievement. However, as an example of a credible long-run investment, consider that the European Investment Bank has recently created the 2020 European Fund for Energy, Climate Change and Infrastructure (“Marguerite Fund”), partnering with national institutional investors with the aim of providing long-term financing of the energy infrastructure with an emphasis on renewables [26]. The Marguerite Fund's innovations are that it is not speculative and that it has a long-run horizon.

Our paper fits in the current literature investigating the environmental policy instruments that stimulate the transition to RES.

The paper proceeds as follows. Section 2 describes materials and methods. Section 3 presents results and discussion. Section 4 concludes and discusses the policy implications.

2. Materials and methods

2.1. The model structure

In this paper, we build a micro-founded DSGE model with energy sectors facing environmental issues in line with the recent literature ([1,5,7,20,51,61]; among the others). The RES deployment is implemented by a government balanced environmental policy instrument, which is a carbon tax entirely financing a RES development policy. This latter is modeled in two variants: a technology-push subsidy to knowledge capital (variant A) or a demand-pull price subsidy (variant B).

Our economy's supply side is comprised of four sectors; one is a final consumer goods sector and three intermediate goods sectors[2]:

$$\begin{aligned} Y_t &= A_t^y \left(N_t^y\right)^{\alpha} \left(K_{t-1}^y\right)^{\beta} \left(E_t\right)^{1-\alpha-\beta} \\ E_t &= A_t^e \left(\eta (ER)_t^{-\varepsilon} + \zeta (EF)_t^{-\varepsilon}\right)^{-\frac{1}{\varepsilon}} \\ (EF)_t &= A_t^{ef} \left(N_t^{ef}\right)^{\theta} \left(K_{t-1}^{ef}\right)^{\vartheta} \left(S_{t-1}\right)^{1-\theta-\vartheta} \\ (ER)_t &= A_t^{er} \left(N_t^{er}\right)^{\iota} \left(K_{t-1}^{er}\right)^{\kappa} \left(K_{t-1}^{g}\right)^{1-\iota-\kappa} \end{aligned} \tag{1}$$

Households are the firms' owners, sell the productive factors to the firms and receive the corresponding value of marginal productivities. The sectorial total factor productivities (TFP) are represented by $A_t^i (i = y,\ e,\ ef,\ er)$, whose law of motion is described by an AR(1) process with zero mean and uncorrelated residuals.

The final output, Y_t, is produced competitively with a constant returns to scale technology according to a Cobb-Douglas production function making use of the three inputs of labor, N_t^y, private capital, K_{t-1}^y, and energy services E_t.

The first intermediate goods sector is represented by the energy sector, which sells energy competitively and is based on clean and dirty inputs. The former are RES $(ER)_t$, with a share η, whereas the latter are fossil fuels $(EF)_t$, with a share ζ. Following Acemoglu et al. [1] and Argentiero et al. [7]; we assume that these inputs are substitutable according to a CES production function.[3]

The second intermediate goods sector is represented by the fossil fuel sector which produces its output competitively with a constant returns to scale technology and is represented by a mining firm employing private capital, K_{t-1}^{ef}, labor, N_t^{ef} and a stock of deposit, S_{t-1}, from which fossil fuel is extracted.

The third intermediate goods sector is represented by the RES sector, with a RES producer in a regime of a perfectly competitive market with constant returns to scale technology. The corresponding production function (Equation (4)) differs from the traditional two-factor function commonly used in the literature because it explicitly considers beyond the fixed private capital and

[1] Biomass strongly contributes to meet residential energy needs in under developed and developing countries and to increase rural employment, given that biomass production is labor intensive [54].

[2] The detailed model and the analytical derivation of the optimality conditions are reported in Appendix.

[3] In the energy production function $\varepsilon = \frac{1-\sigma}{\sigma}$, with σ corresponding to the elasticity of substitution between RES and fossil fuels.

labor, K^{er}_{t-1} and N^{er}_t, a specific knowledge capital stock [18], K^{g}_{t-1}, as input, which represents the cumulated investment in R&D. The reason for including this immaterial capital separate from other inputs is that private fixed capital input is not a perfect substitute for the knowledge capital stock in the RES sector. Indeed, innovation driven by R&D represents a key device in order to spur clean energy (see among others [28]). The presence of knowledge spillovers related to K^{g}_{t-1} generates a further market failure together with the pollution produced by the fossil fuel sector. Hence a public intervention is needed. The first policy variant A assumes that the government supports the knowledge capital, K^{g}_{t-1}, through a monetary subsidy, μ^{g}_t, that is entirely financed by a tax on the fossil fuels, which are responsible for dirty emissions. This subsidy acts in supporting the knowledge capital rentals; hence, the resulting RES profit function takes the following form:

$$\Pi^{er}_t = P^{er}_t A^{er}_t \left(N^{er}_t\right)^{\iota} \left(K^{er}_{t-1}\right)^{\kappa} \left(K^{g}_{t-1}\right)^{1-\iota-\kappa} + \left(1-\delta^{er}\right) K^{er}_{t-1} + \left(1-\delta^{er}\right) K^{g}_{t-1} + \\ -W^{er}_t N^{er}_t - R^{er}_t K^{er}_{t-1} - \left(R^{g}_t - \mu^{g}_t\right) K^{g}_{t-1} \tag{2}$$

where W^{er}_t represents the nominal wages, $R^{i}_t (i = er,\ g)$ is the corresponding gross capital rental and $\delta^{i} (i = er,\ g)$ indicates the rate of capital depreciation.

We assume that the price of RES, P^{er}_t, is measured as society's opportunity cost of efficiently deploying RES in the system. For this reason, we consider the LCOE of deploying RES given the best available technologies and the prevailing financial and administrative constraints.

The second policy variant B implies a demand-pull price subsidy, μ^{p}_t, able to support the RES price:

$$\Pi^{er}_t = \left(P^{er}_t + \mu^{p}_t\right) A^{er}_t \left(N^{er}_t\right)^{\iota} \left(K^{er}_{t-1}\right)^{\kappa} \left(K^{g}_{t-1}\right)^{\nu} + \left(1-\delta^{er}\right) K^{er}_{t-1} + \left(1-\delta^{er}\right) K^{g}_{t-1} + \\ -W^{er}_t N^{er}_t - R^{er}_t K^{er}_{t-1} - R^{g}_t K^{g}_{t-1} \tag{3}$$

The technology-push public incentive to investment in R&D and the demand-pull price subsidy are both financed by a carbon tax on fossil fuels, assuming that the government's budget is balanced at each time for both the options. Hence, the entirety of the revenues from environmental taxation can finance either R&D investments (variant A) or a price subsidy of RES (variant B). Thus, public budget constraints differ according to the variant that we consider.

At each time t, in the variant A the following equality holds:

$$\tau(EF)_t = \mu^{g}_t K^{g}_{t-1} \tag{4}$$

where tax revenues on fossil fuels (the left side of the equation) are equal to public investment to the amount of the subsidy on knowledge capital, K^{g}_{t-1} (the right side of the equation).

In the second policy variant B, the government's budget constraint is:

$$\tau(EF)_t = \mu^{p}_t ER_t \tag{5}$$

where tax revenues on fossil fuels (the left side of the equation) are equal to the entire amount of the price subsidy on the RES (the right side of the equation).

The economy's demand side is populated by an infinite number of infinitely living households with preferences defined for the following variables: private consumption C_t and labor services, N_t. These latter are allocated to final output production (N^{y}_t), fossil fuel sector (N^{ef}_t) and RES sector (N^{er}_t) on a period-by-period basis.

Each agent maximizes the expected value of an intertemporal utility function:

$$E_0 \sum\nolimits_{t=0}^{\infty} \rho^t U_t\left(C_t,\ N^{y}_t,\ N^{ef}_t,\ N^{er}_t\right) \tag{6}$$

with ρ^t corresponding to the subjective discount factor under a standard intertemporal resource constraint.

Let the period utility function assume the following CRRA form:

$$U_t = \left(\Upsilon_t \frac{(C_t)^{1-q}}{1-q}\right) - \frac{\left(N^{y}_t\right)^{1+\chi}}{1+\chi} - \frac{\left(N^{ef}_t\right)^{1+\omega}}{1+\omega} - \frac{\left(N^{er}_t\right)^{1+\psi}}{1+\psi} \tag{7}$$

where Υ_t is a taste shifter [59], whose law of motion is described by an AR(1) process with zero mean and uncorrelated residuals.

2.2. Data and estimation

The United Nations Environmental Programme has produced the fourth Global Environment Outlook (GEO-4), presenting four scenarios by 2050 which examine different policy approaches and societal choices at regional and global levels, and their implications for the environment and human well-being [62]. In our paper that investigates RES future, we base the energy market on the "Policy First" scenario.

In order to estimate the model's parameters, to simulate the time series for the key variables of the model and to analyze their dynamics, we use the Metropolis-Hastings algorithm. This econometric procedure belongs to the family of Bayesian estimation methods that are very common in the empirical macroeconomic literature (see among others [15,57]). In particular, our estimation technique is a combination of the maximum likelihood approach with assumptions on prior distributions of the parameters. Moreover, because the model is non-linear in some equations, we have preliminarily linearized and solved it using the Blanchard and Kahn [8] algorithm.

We use DYNARE software[4] to perform all the calculations.

[4] Dynare is a software that is freely available from http://www.dynare.org and has the ability to simulate and estimate economic models.

Table 1
Parameters' definitions.

Parameter	Definition
α	final output elasticity of labor
β	final output elasticity of capital
δ_y	depreciation rate of final output capital
δ_{ef}	depreciation rate of fossil fuels capital
δ_{er}	depreciation rate of RES capital
δ_g	depreciation rate of knowledge capital
δ_s	depreciation rate of fossil deposit
ε	elasticity of substitution between RES and fossil fuels
ζ	fossil fuels share in energy production
η	RES share in energy production
θ	fossil fuels elasticity of labor
ϑ	fossil fuels elasticity of capital
ι	RES elasticity of labor
κ	RES elasticity of private capital
q	Coefficient of relative risk aversion
φ^y	Persistence in final output TFP
φ^e	Persistence in energy TFP
φ^{ef}	Persistence in fossil fuels TFP
φ^{er}	Persistence in RES TFP
φ^{Γ}	Persistence in taste shifter
ψ	Inverse of RES Frisch elasticity of labor supply
ω	Inverse of fossil fuels Frisch elasticity of labor supply
χ	Inverse of final output Frisch elasticity of labor supply
ρ	Intertemporal discount factor
τ	Environmental tax rate on fossil fuels' production

Below, we summarize the measurement equations considered, that is the relationships between the model variables (on the right side) and the data (on the left side):

$$\begin{bmatrix} \Delta\ln C_t \\ \Delta\ln E_t \\ \Delta\ln(EF)_t \\ \Delta\ln(ER)_t \\ \Delta\ln Y_t \end{bmatrix} = \begin{bmatrix} \Gamma^{(A)} \\ \Gamma^{(A)} \\ \Gamma^{(A)} \\ \Gamma^{(A)} \\ \Gamma^{(A)} \end{bmatrix} + 100* \begin{bmatrix} c_t - c_{t-1} \\ e_t - e_{t-1} \\ (ef)_t - (ef)_{t-1} \\ (er)_t - (er)_{t-1} \\ y_t - y_{t-1} \end{bmatrix} \lim_{x\to\infty}$$

$\Delta\ln C_t$ is private consumption growth expressed in percentage terms, $\Delta\ln E_t$ is gross inland energy consumption[5] growth expressed in percentage terms, $\Delta\ln(EF)_t$ is fossil fuels' gross inland consumption growth expressed in percentage terms, $\Delta\ln(ER)_t$ is RES inland consumption growth expressed in percentage terms and $\Delta\ln Y_t$ is real GDP growth expressed in percentage terms. Moreover, we consider a common annual trend growth rate among the variables, $\Gamma^{(A)}$, which is the annual trend growth rate common to private consumption, GDP, energy, fossil fuel and RES, expressed in percentage terms $(100*\ln\Gamma)$. In line with the literature (see among others [17,57], we assume that all non-stationary real variables exhibit a common trend growth rate that we calibrate with a value of 1.6, which is consistent with the potential output growth rate data for the EU-15. Finally, the third vector indicates the corresponding log-linearized variables around their steady state balanced growth path. The sources of our data for the period 1995–2015 at an annual frequency are the Ameco database [4] for private consumption and final output and the Eurostat database [27] for energy variables.

More specifically, private consumption C_t is measured according to the total final consumption expenditure of households for EU-15 countries in constant 2010 prices. Energy services, E_t, are measured according to the EU-15's gross inland energy consumption (thousand tons of oil equivalent, TOE). Fossil fuels, $(EF)_t$, are measured according to the sum of gross inland consumption of solid fuels, total petroleum products, gas and nuclear heat for the EU-15 countries (TOE). RES, $(ER)_t$, are measured according to the EU-15's energy gross inland consumption for RES (TOE), including wind, solar photovoltaic and biomass. Final output, Y_t, is measured according the EU-15's real GDP in constant 2010 prices.

The choice of these observable variables is motivated by this paper's main purpose, i.e., the construction of simulated time series for RES and fossil fuel quantities and prices, in the presence of public policies for RES development. In this regard, the use of gross inland consumption data (inclusive of imported energy) instead of primary production appears to be more realistic and consistent with European energy markets, which import a large share of fossil fuels.[6] Furthermore, real GDP and private consumption data are good measures of economic activity levels, which are able to influence both energy demand and price for RES and fossil fuels.

2.3. The model calibration

The parameters of the theoretical model together with their definitions are shown in Table 1.

The prior densities (i.e., the calibrated values) are consistent with the domain of the parameters and are shown in tables 2, 3, 4 and 5 in Appendix. Then, we use the data on the observable variables (private consumption, energy, RES, fossil fuels and final output) conditionally to the model to estimate the posterior values of the structural parameters.[7]

The final output production function elasticities α and β are distributed according to a beta random variable with mean equal to the average shares of wages and capital rents on the EU-15 GDP respectively, with a standard deviation of 0.05. Moreover, fossil fuel and RES production function elasticities $(\theta, \vartheta, \iota, \kappa)$ follow a beta distribution with mean equal to the average production shares of administrative costs for labor (θ, ι) and average production shares of capital costs (ϑ, κ) respectively, with a standard deviation of 0.1 for fossil fuels and 0.5 for RES. The calibration for wage and capital rental shares in the fossil fuels sector is consistent with the World Input Output Database [60] data for coke, refined petroleum and nuclear fuel in the EU-15. For the RES industry, we assume the same values of the fossil fuels, but with higher standard deviations in order to loosen the conditioning of prior values on the posterior ones. Capital and fossil deposits' depreciation rates $(\delta^y, \delta^{ef}, \delta^{er}, \delta^g, \delta^s)$ are distributed according to a beta random variable with mean equal to 0.1, a value consistent with a quarterly rate of 0.025, that is a commonly adopted value in the literature [56], with standard deviations of 0.05 for final output capital and 0.1 for the others.

The shares of fossil fuels and RES in the energy production functions, ζ and η, follow a beta distribution with mean equal to 0.88 and 0.12, respectively, which are the average shares of fossil fuels and RES in energy production for the EU from 1995 to 2015 [27], whereas the elasticity of substitution between RES and fossil fuels follows a gamma distribution with a mean of 0.45, which is the value of the estimated elasticity of substitution between clean and dirty energies in the EU [53].

The coefficient of relative risk aversion, q, which is the inverse of

[5] Gross inland consumption is calculated as follows: primary production + recovered products + total imports + variations of stocks - total exports - bunkers. It corresponds to the sum of final consumption, distribution losses, transformation losses and statistical differences [27].

[6] Europe imports more than half the energy it consumes, mainly from Saudi Arabia and Russia, and import dependency is particularly high for crude oil and natural gas [50].

[7] The comparison between posterior estimates of the parameters and the prior densities is discussed in the next section.

the intertemporal elasticity of substitution of consumption, is normally distributed with a mean of 1.1, a value consistent with the macroeconomic literature on the estimated DSGE models [57], and a standard deviation of 0.5, whereas the inverse of the Frisch elasticities of labor supply, ψ, ω and χ, follow a gamma distribution with mean equal to 2 with a standard deviation of 0.75, following Smets and Wouters [56].

The persistence coefficients for the stochastic processes related to the TFPs and taste shifter are distributed according to a beta distribution with mean equal to 0.85, following the real business cycle literature [9,41,56], and standard deviations equal to 0.10.

The intertemporal discount factor ρ follows a beta distribution with a mean of 0.92, implying a steady state value of 9%[8] for the private capital rental, according to *Euler Equations*, and a standard deviation of 0.05.

The standard errors of TFP and taste shifter shocks follow an inverse gamma distribution with means equal respectively to 0.4 and 0.2 and standard deviations set to 2 for both the variables, following Smets and Wouters [56].

The environmental tax rate, τ, follows a gamma distribution with a standard deviation of 0.1 and a mean of 575.15€/TOE, which is the average effective tax rate per TOE on gasoline and diesel for road use, assumed as proxies of the environmental tax rate, in France, Italy and Germany for the sample considered (authors' elaborations on OECD, 2015, data).

3. Results and discussion

In this section we show the results deriving from the parameter estimation according to the Bayesian technique discussed in the previous section. Then, we discuss the dynamic response of the model's variables in the presence of supply and demand shocks under both the policy options considered through the impulse response functions. Finally, we present the simulated time series for the RES and fossil fuels quantities and prices generated for the EU-15 through the MCMC method over the 36 years represented in the sample for 1995–2030.

3.1. Posterior distributions

The fifth and sixth columns of the tables 2, 3, 4 and 5 in Appendix show the posterior means and a 90% credible interval for the estimated parameters obtained by the Metropolis-Hastings algorithm compared to their prior distributions for the variant A (tables 2 and 3), i.e. a policy intervention based on a support to knowledge capital, and variant B (tables 4 and 5), i.e. the presence of a monetary subsidy on RES price.[9]

The log-marginal value of the likelihood for the first policy variant A is −356.89, whereas for the second variant B is −311.12. In order to compare these policy scenarios, we build the Bayes factor through the Laplace method to approximate the integrated likelihood [40] and [45], that is:

$$B_{p,g} = 2\ln\left[\frac{f\left(Y\middle|\mu_p\right)}{f\left(Y\middle|\mu_g\right)}\right] \tag{8}$$

with μ_p and μ_g indicating respectively the price subsidy model and the R&D subsidy model where

$$f(Y|\mu_m) = \int f(Y|\theta_m,\ \mu_m)\, f(\theta_m|\mu_m)\, d\theta_m m = p,g \tag{9}$$

The Bayes factor, $B_{p,g}$, is equal to 91.54, which strongly supports the specification with a monetary subsidy on the RES price. This result is not surprising, since in the EU-15 countries the RES support is mainly achieved through price subsidy policies.

The posterior estimated values for final output sector are higher than the prior labor elasticities and lower than the prior capital elasticities, thus indicating a labor-intensive feature of this sector, whereas fossil fuels and RES sectors are more capital-intensive.

Moreover, in variant A, we observe a strong increase of η from a prior of 0.12 to a posterior of more than 0.19 (and hence a decrease of ζ from a prior of 0.88 to a posterior of 0.80), whereas in variant B the share η is quite stable.

The values of the elasticity of substitution between RES and fossil fuels, the capital depreciation rates, the environmental tax rate and the intertemporal discount factor exhibit a positive shift in both the variants.

Looking at the households' sector parameters, the inverse of Frisch elasticities of labor supply is higher than the prior values, with greater values for the fossil fuels and RES sectors and slightly lower values for the final output sector. These last results show that there is greater labor market flexibility in the final output sector with respect to the energy sectors. The posterior estimated coefficient of the relative risk aversion is lower than the prior value in both the variants (from 1.1 to 0.83 with an R&D subsidy and from 1.1 to 0.96 with a price support), thus showing a smaller degree of risk aversion than assumed a priori.

A closer inspection to the exogenous processes shows that the size of the autoregressive coefficients is confirmed, even though in both of the variants the taste shifter is less persistent than in the prior estimates, energy TFP is always more persistent with respect to the prior values, whereas fossil fuels and RES TFPs are more persistent in the policy variant supporting knowledge capital and less persistent when a price subsidy is present. Regarding final output, it is interesting to note that in both the variants, the final output TFP persistence exhibits a positive shift that is always greater than the persistence of the taste shifters. This evidence confirms the economic features of TFP and taste shocks. The formers are typically more persistent, dealing with the supply-side of the economy, whereas the latter, which are demand shocks, deplete their effects in the short-term [9].

The standard errors of TFP and taste shifter shocks show a posterior mean that is substantially consistent with the prior distributions for consumption and final output, whereas for energy sectors these values are lower. This result sharpens a lower volatility for TFP in the energy markets compared with the results for final output[10].

Finally, the posterior estimates of the trend growth rate are slightly lower than their prior values in both of the variants.

3.2. Model dynamics

In this section, we discuss the dynamic response of the relevant variables when the economy is hit by stochastic shocks on TFPs and

[8] This value is the net private capital rate of the EU-15 from 1995 to 2016 (source: authors' elaborations on data from Refs. [4] and [27]).

[9] Following Smets and Wouters [57]; to evaluate the sensitivity of the estimation results to our assumptions on prior estimates, we have increased the standard errors of the prior distributions of the parameters by 50%. Overall, the estimation results are very similar. These results are available upon request.

[10] Although at a first sight this result may seem counterintuitive, this is not the case. In fact, in this model the energy sectors are intermediate sectors with respect to the final output sector. Hence, this latter incorporates the volatility of its own shocks and the one of the intermediate sectors, with a resulting higher total volatility.

taste shifter, namely impulse response functions (IRFs).

Note that for all of the IRFs, the size of the standard deviations of the stochastic shocks and the variables' responses relate to the posterior-average of the IRFs for each draw of the MCMC algorithm, together with 95% confidence intervals.[11] Moreover, because the variables are expressed in logs, the measures of the responses can be read as elasticities.

Next, we analyze (through the MCMC algorithm) the dynamic behavior of both prices and quantities of fossil fuels and RES for the two alternative policy interventions: i.e., monetary subsidies on knowledge capital (variant A) and RES price (variant B).

We compare the Bayesian IRFs for a TFP shock on final output in variants A and B, as shown in Figures (5) and (6) in Appendix.

In both scenarios, a positive technology shock to final output generates an increase in production and consumption through a positive shift of final goods' supply curves and productive factors' demand curves. In particular, the increased TFP generates a positive shift of energy demand and price, along with increases in both fossil fuels and RES prices, thus inducing a growth in their quantities. Furthermore, the increase in the RES quantity and the effects on energy price and quantity are different in the two energy policy variants. In both variants, the growth of RES price determines a rise in three marginal productivities (real remunerations of the productive factors) and hence an increase in labor, private and knowledge capital. However, in variant A, the public support to knowledge capital through a subsidy on the corresponding rentals generates a higher increase for RES than the variant B.

Therefore, in variant A, energy production and price increase more than in variant B.

We then analyze the IRFs when a positive shock hits the energy sector (Figures (7) and (8) in Appendix).

If energy is more productive, both fossil fuels and RES experience increased prices and quantities, although with different sizes in the two variants. In variant A, the increase of RES in the energy sector - in terms of increased quantity and price - is greater than variant B, as in the case of final output TFP shock.

We show IRFs in the presence of a TFP shock in the fossil-fuel sector in Figures (9) and (10) in Appendix.

In this case, the growth of fossil fuels' TFP generates an increase in fossil fuels' supply curve, thus determining a decrease in fossil fuels' price. Moreover, this shock determines a reduction in RES production by different amounts in the two variants, due to the reallocation of private capital and labor toward the fossil-fuel sector, which is more productive. The decrease of RES production generates a positive growth of RES price. In variant A, the decrease in RES is lower because the reduction of private capital and labor is partially offset by the increase in knowledge capital determined by the growth of fiscal revenues coming from environmental taxation. In variant B, the reduction of RES is higher than in variant A and the only effect of the increase in the monetary subsidy related to the growth of environmental taxation is to slow down the reduction in profits. The overall effect on energy production is positive and therefore its price decreases.

We analyze the IRFs describing a TFP shock in the RES sector in Figures (11) and (12) in Appendix.

A positive growth in RES TFP has the ability to increase RES production of different amounts for each of the two variants. In both of them the decrease of environmental fiscal revenues, due to the contraction of fossil-fuel production, generates a reduction in the subsidies. In fact, a RES TFP shock determines a reallocation of private capital and labor of fossil fuel sector toward the RES sector.

In both of the variants, RES and energy prices decrease, whereas energy production increases at different magnitudes.

We analyze the IRFs in the presence of a demand shock on the preferences in Figures (13) and (14) in Appendix.

The response of the variables in this context has common features to the case of the final output TFP shock. In particular, for this shock the positive shift of the productive factors' demand curves is determined by tastes, whose growth determines an increase of private consumption and hence a higher production through an enhanced use of the inputs.

Finally, we analyze the simulated price parity points and the respective share of fossil fuels and RES with a 95% confidence interval for the two energy policy variants set forth in Figs. (1) and (2).

The time series are generated for the EU-15 through the MCMC method over the 36 years represented in the sample for 1995–2030. For each year, we draw 200,000 realizations of the stochastic shocks. Next, we take the expected value of this sequence as the corresponding value for each year.[12] The prices are expressed in Euro/Kwh, whereas the shares are in percentage terms.

The presence of a supported stock of knowledge capital in the RES production function can anticipate the price parity between RES and fossil fuels. Indeed, according to our empirical results for the policy variant A, this parity is expected to occur around 2019, whereas in the case of the monetary subsidy to RES price, parity is expected to occur around 2028. In addition, given the model structure, the price parity level is lower in variant A.

Furthermore, in variant A EU-15 is expected to reach a RES average share of 26% in 2020 and 31% in 2030, whereas in variant B these values are figured to be 21% and 26% respectively (Figs. 3 and 4).

To make RES competitive in the electricity market, public support is essential. In this framework, our simulations show a support scheme that promotes RES development based on a carbon tax and a public subsidy, financing a knowledge capital stock, as an input into the RES production function, generates better results compared to the most widely used price-based support scheme, i.e., carbon taxes and subsidies allocated to RES producers. More specifically, knowledge capital stock captures both the actual value of policy commitment in monetary resources and the value of innovation, which creates a favorable administrative framework for investment decisions in the electricity markets. This is the key point of our research. We address the problem of stimulating RES acting on the quality of environmental public policies over time. To this end, our model endogenously determines the stock of public capital in the RES sector, the achievement of price parity and the corresponding determination of the share of RES and fossil fuels, whereas in most of the current literature, this achievement is determined by implementing an exogenous experience curve approach [12,48].

4. Conclusions and policy implications

This paper shows an alternative cost-effective incentive mechanism for RES deployment in the Euro-area. We have estimated a DSGE model using Bayesian techniques for the EU-15 area over the period 1995–2015 which includes explicitly a carbon tax and a RES subsidy scheme modeled in two variants: technology-push measures in terms of a subsidy to knowledge capital and demand-pull measures as a price subsidy. The inferential procedure is based on the MCMC methods, allowing to estimate both the model

[11] The confidence intervals have been computed as the 2.5 and 97.5 percentiles of the empirical distributions obtained by the algorithm.

[12] Hence, our estimate for each year is the average of all the trajectories obtained, whereas the confidence interval has been calculated, as for the IRFs, as the 2.5 and 97.5 percentiles of the empirical distributions generated by the algorithm.

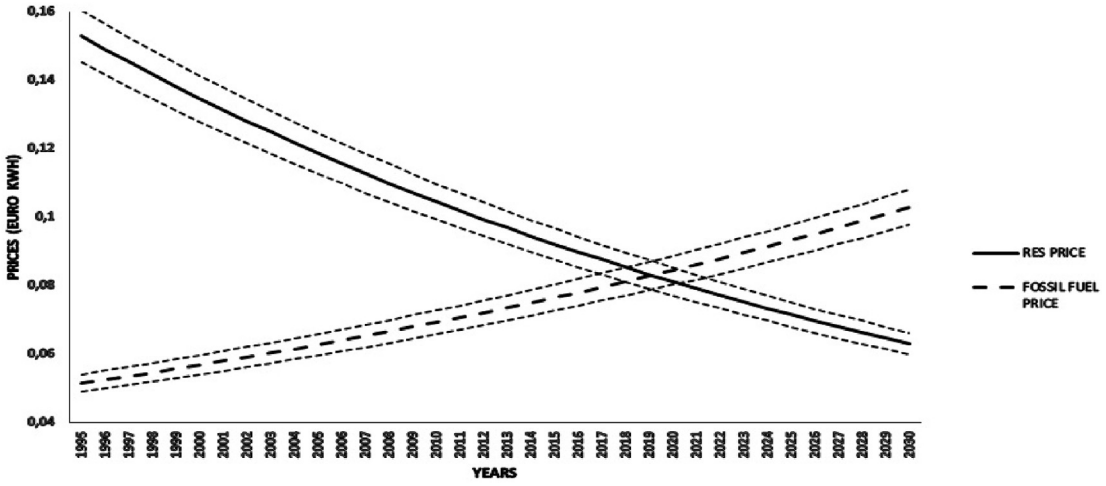

Fig. 1. Price parity variant A.

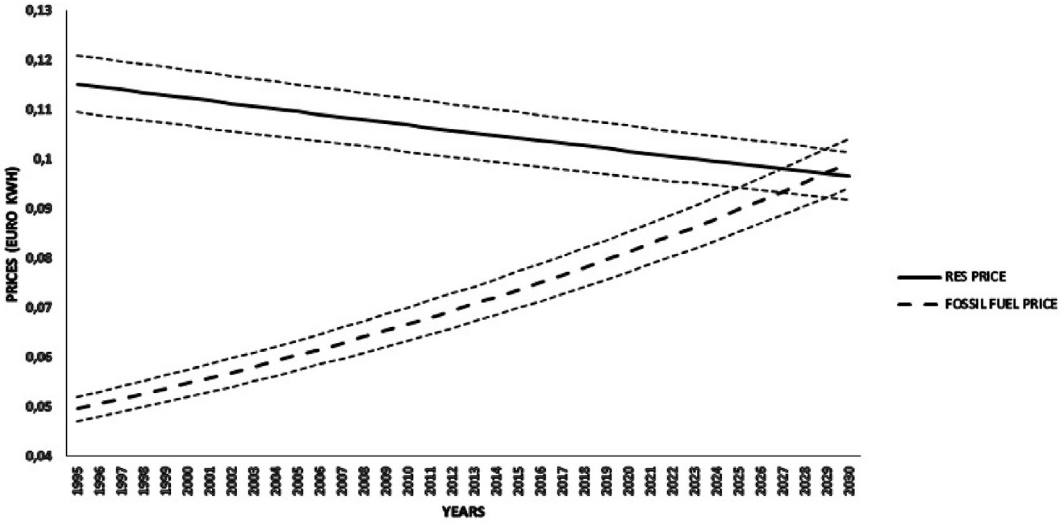

Fig. 2. Price parity variant B.

parameters and the dynamics of some relevant variables, i.e., fossil fuels price and RES price.

Regarding the RES targets of 20% and 27% in energy consumption to be achieved in the years 2020 and 2030, we find that the technology-push measure achieves a simulated share of 26% and 31% in these years, respectively, while the demand-pull measure achieves a share of 21% and 26%, respectively. This implies that a subsidy to knowledge capital (technology-push measure) is more effective compared to a monetary subsidy to the RES price (demand-pull measure) for the RES long-run development. In other words, there could be a cost savings in the case of technology-push measure, used to achieve exactly the EU target.

Our results show that RES production increases more with a policy intervention based on a technology-push measure than with demand-pull measures, both under supply and demand shocks on final output. Moreover, when the energy sector is more productive, the technology-push measure spurs RES production in a more effective way compared to demand pull measure.

Finally, we have investigated the issue of RES price parity, which is an important milestone for RES deployment. Comparing the two RES support measures, we find that RES price parity occurs sooner in the case of technology-push measure, approximately 2019, compared to demand-pull measures which will occur approximately in 2028. Moreover, the strength of our results is that price parity is endogenously determined by the model, contrary to most of the literature, which deploys price parity calculation based on exogenous assumptions about LCOE and RES learning rates.

The findings of this study, related to EU countries, suggest to deeper the analysis, applying this model to a larger sample of countries, including developing countries. However, this would require a further analysis of the RES support mechanisms implemented in such countries, which is left for future research.

This paper has two policy implications. First, providing a quantitative measure of the relative effectiveness of alternative policy measures, we show that governments can encourage RES deployment implementing technology-push measures that reduce the private cost of producing innovation in RES technologies. For RES to be competitive in the energy markets, a number of technologies' improvements are required, such as energy storage which mitigate the variability and unpredictability of RES. Carbon taxes are not high enough to provide incentives to use RES technologies. Both the low level of maturity of some RES technologies requiring large investments, and the high regulatory uncertainty, limit the

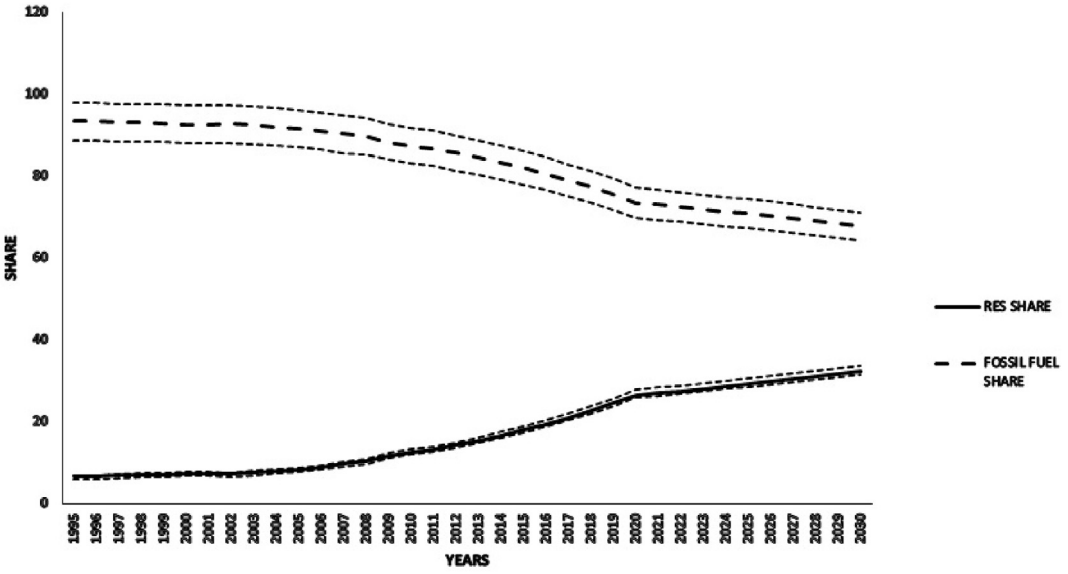

Fig. 3. Share of fossil fuels and RES, variant A.

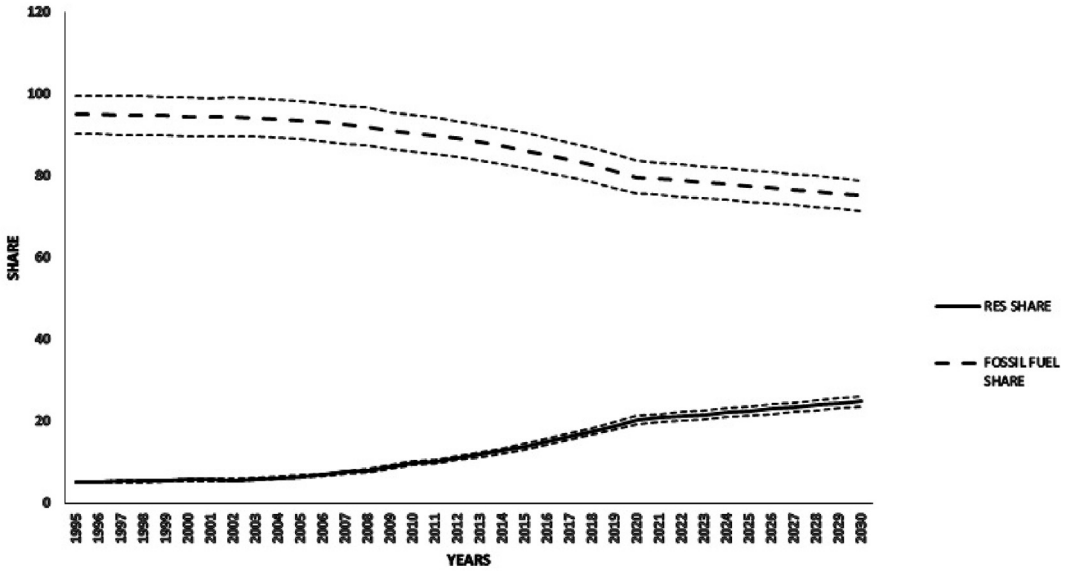

Fig. 4. Share of fossil fuels and RES, variant B.

RES share in the energy markets. Therefore, RES deployment requires subsidies' policies that carefully balance demand-pull and technology-push mechanisms. Policy makers can evaluate the cost implications for the final consumers of each policy measure and assess their monetary relevance with respect to the policy preferences.

Second, we provide a simulation of the RES price parity occurrence, showing that the price parity point in the energy system can vary according to the RES support policies implemented. RES market penetration would lead to decline in the costs of RES, moving to the price parity. Our analysis of price parity, providing meaningful results, could help policy makers to make more informed decisions.

In conclusion, given that investments in RES technologies needs both a long-term credible policy makers commitment and adequate institutional framework for free market development, our paper provides a timetable for such actions. Indeed, without an initial support, it would not be possible to ensure the adequate RES deployment necessary to spur the positive effects of learning by doing and the development of new competitive technologies. However, we recall that economic analysis has long recognized that as competitive markets develop, they work effectively with adequate institutional rules without a direct public intervention. In this sense, our findings show when the times will be mature for RES to be the new protagonist of our future sustainable world.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.renene.2017.12.057.

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